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MODELING REINFORCED CONCRETE FOR IMPACT LOADING: PHASE I

Report No. 86-216-K

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ABSTRACT

This report presents the findings of a literature search on the validity and applicability of using scaled reinforced concrete models for predicting full scale prototype behaviour under impact conditions. From the literature search, it is concluded that scaling laws do exist for modeling reinforced concrete. Of primary importance for the case of impact loading, where large deformations are expected, is that the material for the full scale prototype and scale models have identical stress-strain characteristics. This conclusion is supported by the results of missile impact tests on reinforced concrete panels; however, for the specific case of impact during free drop tests, limited information is available. For this reason, an experimental program consisting of a series of drop tests on reinforced concrete models of different sizes is proposed.

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1.0 INTRODUCTION

In 1983, Ontario Hydro began investigating the possibility of using concrete casks as a means of storing, transporting and disposing of irradiated fuel. As part of this investigation, Civil Research built and tested a one-half scale model of a prototype concrete cask that had been designed by the Civil Design and Nuclear Materials Management Departments. The testing program was undertaken to assess the cask's compliance with International Atomic Energy Agency (IAEA) licensing regulations for the transportation of a Type B package, and included drop tests from heights of 9 m and 1 m followed by an exposure to an open fire.

The testing program was completed in September 1984 and the results indicated a successful structural performance of the model/1/. It was expected that full containment of a radioactive payload would have been maintained, and an effective radiation shield remained after all tests/1/. However, a definitive statement as to whether or not the prototype concrete cask would have passed the IAEA licensing tests could not be made, in part due to a question of the validity of extrapolating results from the one-half scale concrete cask model to the full-scale prototype design under such extreme impact conditions.

In response to this question, it was proposed that an experimental program be undertaken, with the specific purpose of investigating and demonstrating that concrete materials and structures can be adequately scaled under severe impact (drop test) conditions. The investigation work (Phase I) includes a literature search on the validity of scaling laws in reinforced concrete, and the proposal of a generic test program which will

verify the literature search findings. Demonstration work (Phase II) includes the performance and analysis of the proposed generic experimental program.

The purpose of this report is to present the findings of Phase I - the literature search and the proposed experimental program. The literature search includes a study of the scaling laws for models, and a summary of the findings of previous investigations into reinforced concrete scale models under impact conditions. The concerns and experimental approach of previous investigators into the scale modeling of concrete are detailed and elaborated upon. Based on these findings, an experimental program is proposed which involves testing a series of reinforced concrete models of different scales. The test series is designed to investigate the validity of scaling laws in reinforced concrete under extreme impact conditions in order to gain confidence in relating damage results in small scale models to a full scale prototype design.

2.0 LITERATURE SEARCH

The primary objective of the literature search was to investigate the validity of scaling reinforced concrete and, in particular to determine if special considerations are necessary for the case of impact loading. A secondary objective of the literature search was to gather information on the instrumentation and methods of analysis used to monitor, record and predict the behaviour of the test specimens. This secondary objective will help answer questions which will arise in planning the details for the proposed experimental test program.

The sources for the literature search were concentrated in four principal areas. The first area investigated was on scaling laws as they apply to models in general, with particular attention focused on the applicability of these scaling laws to the specific cases of concrete models and scaling under impact conditions.

Missile impact tests on reinforced concrete slabs provided a second major source of information. Some of these tests involved models at a single scale, which provided information on the practical considerations of building scale models in reinforced concrete. Other missile impact tests which were performed on models of different scales were very useful in validating the scaling laws for models of different size.

A third source of information researched was on drop tests. Specifically, information on drop tests of concrete models was

desired. In general, few sources were available, and therefore, additional reference was made to scale model drop tests of steel containers.

In reading through the sources listed above, a common concern among many researchers was the effect of strain rate on the results. For this reason, a fourth source of information researched was on the effect of high strain rates on the material response of both steel and concrete.

From the aforementioned four principal sources, the information was gathered, sorted, and organized into groups best suited for satisfying the objectives of the literature search. Five areas were chosen and are discussed as follows:

(i) Scaling laws for models, with particular attention to concrete models under impact conditions.

(ii) Materials similitude in scaling reinforced concrete.

(iii) Results from impact tests at different scales.

(iv) Strain-rate dependency of material properties.

(v) Methods of instrumentation and analysis.

2.1 Scaling Laws

Model analysis, regardless of the material of the model, is governed by the requirement of similitude. For a valid model there must be materials and geometric similitude. Materials (behaviour) similitude, in principle, allows different materials to be used for model and prototype, as long as at any given load the stress and strain in model and prototype are related by a constant stress scale factor, S_σ, and a constant strain scale factor, S_ε. Typically, these criteria are applicable to elastic modeling. For test cases where the material is of an inelastic nature and will be subjected to large deformations, such as in the case of drop tests, one is constrained to keeping the material behaviour identical ($S_\sigma = S_\varepsilon = 1$) in order to fully model the behaviour of the system/2,3,4,5,6,7/. This technique is commonly referred to as replica scaling. For geometric similitude, as defined by the scaling factor S_ℓ, it is necessary that all linear dimensions of both the specimen and the load application system be scaled down from the corresponding dimensions of the prototype by a constant ratio $1/S_\ell$.

Having set the scaling factors S_σ and S_ε equal to one and leaving the geometric scaling factor S_ℓ as an unknown, a dimensional analysis of the stress and deformation establishes

all other relationships between prototype and model (See Table 1).

In addition to the items in Table 1, an important parameter for modeling the crushing response of concrete is the ratio of the crushing energy to the impact kinetic energy, Ø, which is defined as follows/5/:

$$\emptyset = \frac{\gamma d^2}{mv^2}$$

Ø = a dimensionless group
γ = the specific surface energy of concrete matrix
d = the diameter of the crushed particle
m = the mass of the model
v = the impact velocity of the model

In order to satisfy Ø, it is required that both the particle diameter and specific surface energy of the model concrete be scaled by $1/S_\ell$. The particle diameter requirement is easily satisfied by scaling the maximum coarse aggregate size. However, it is very difficult to control the specific surface energy of a concrete, since specific surface energy is a function of the cement paste, aggregate type, and type of bond between paste and aggregate/8/. These factors are not scalable since the cement and aggregate type remain the same for the models and the prototype.

Additionally, Table 1 indicates that the acceleration due to gravity should be scaled. The consequence of not scaling gravity is negligible with respect to the effect on dead load, since in all cases the dead load is much smaller than the impact loading. As well, in relation to drop tests, it is necessary that gravity not change so that the impact velocity remains constant for all the models. Several of the items in Table 1, such as the magnitude and duration of the impact force, the deceleration, and the strain-rate, are beyond our control. However, with respect to investigating the scale effects of drop testing models, these are all items which we do not want to control, as the purpose of a test series would be to investigate how these non-scaled items will affect the test results.

2.2 Materials Similitude in Scaling Reinforced Concrete

2.2.1 Concrete

Replica scaling was identified in the previous section as being necessary for correctly modeling concrete behaviour. The model and prototype concrete should behave identically with respect to:

1 - Compressive stress-strain behaviour

2 - Tensile stress-strain behaviour

3 - Bond characteristics between the steel and concrete

4 - Aggregate interlock behaviour at a crack interface

5 - Crushing strength under impact loading

The conclusion of most researchers is that scaling coarse aggregate sizes represents the best compromise for achieving replica scaling. It is regarded as a compromise because the items listed above are affected in opposing ways by scaling the coarse aggregate. For example, in order to keep the bond characteristics and aggregate interlock behaviour (items 3 and 4) the same in both the model and prototype, the maximum coarse aggregate size must be scaled/2,4/. On the other hand, the fact that the aggregate is scaled means that the crushing strength (item 5) will not be the same in the model and prototype, since impact resistance is significantly improved by a smaller maximum size of aggregate/8/. With respect to the effect of maximum aggregate sizes on compressive behaviour (item 1), some researchers have found that scaling maximum coarse aggregate size does not significantly affect the compressive strength of concrete/3,9/. Other researchers qualify this statement by adding that the effect is negligible only at high water-to-cement ratios/10,11,12,13/. This behaviour is partly explained by noting that although an increase in the fine to coarse aggregate ratio can increase the strength due to less bleeding, this may be offset or even reversed by an increase in voids due to the low coarse aggregate content/10/.

The effect of maximum aggregate size on tensile strength is not clear. In one case/9/, it has been observed that the addition of coarse aggregate to mortar reduces the flexural strength. However, this observation is contradicted by another researcher/10/, who observed no measurable effect on the modulus of rupture or split tensile strength due to aggregate sizes ranging from 9.5 mm (3/8") to 63.5 mm (2-1/2").

The preceding discussion serves to illustrate the trade-offs involved in scaling the coarse aggregate for model concrete. It is recognized that the strength properties of the concrete are of greater importance than bond characteristics, aggregate interlock, etc.; however, the prevalent conclusion held by the researchers studied is that the best replicate model concrete is attained by scaling the coarse aggregate sizes. This procedure effectively satisfies the bond characteristic and aggregate interlock parameters, and if the properties of compressive and

tensile strength are adversely affected, then other concrete mix parameters such as water to cementing materials ratio, fly-ash content, etc. could be modified to adjust these properties.

2.2.2 Steel

It is also important for the reinforcing steel to be modeled correctly. Model steel should not only have the same stress-strain characteristics, it should also have the same bond characteristics/2,3,4,14/. Replicating these characteristics is necessary so that the ultimate bond failure loads and cracking behaviour, including size and distribution of cracks, are simulated. In the case of relatively large models, simulating bond is not a problem since steel with the same lug configurations as for the prototype can be accommodated. If the models are small then one may be required to use wire fabric, which has indentations (as opposed to lugs), or smooth wire. In the case of smooth wire some cold drawing and annealing process may be necessary to achieve the same stress-strain characteristics and in addition some kind of deformations will have to be made on the bars to simulate the bond/2,14/. Scaled spacing and/or distribution of the rebars is a requirement of geometric scaling, and it is especially important when the model is expected to experience uniform cracking or significant dowel action of the bars.

2.2.3 Effect on Non-Identical Properties

Should the materials in the model and prototype not have exactly the same stress-strain behaviour, bonding characteristics, etc, the influence on the results of the model tests will depend on the design of the model and the loading conditions. If the model is a lightly reinforced section, which will be loaded past yielding, then the exact modeling of the concrete properties is not as critical as modeling the steel correctly, since the ultimate strength is governed by steel yielding/2/. On the other hand, if the model is very heavily reinforced and the principal failure is due to concrete crushing, then the concrete must be exactly modeled/2,15/.

In the case of drop tests, there is a combination of both of these types of failures. There will definitely be crushing of concrete in the impact zone, and depending on the shape of the model there may also be significant bending and tension in other areas of the model/1/. For this reason, both the steel and the concrete properties of the prototype must be precisely modeled.

2.3 Impact Tests on Reinforced Concrete Models at Different Scales

Some of the most useful information for determining the validity of scaling concrete came from the case studies of tests done on different size models/16,17,18/. In pipe missile experiments prepared for the Electric Power Research Institute (EPRI), full scale and 1/6.4 scale models ($S_\ell = 6.4$) were tested/16/. These tests showed good scaled agreement between perforation depths (ie, $d_{model} = 1/S_\ell \cdot d_{prot}$), which would mean that in terms of strain, the relationship is 1:1. There was also good agreement in the cracking pattern and degree of backface scabbing.

In another series of tests also done for EPRI, in which full scale turbine impact on concrete panels was modeled with 1/11 scale models, similar results were obtained/17/. There was good scaled correspondence between perforation depths and cracking patterns. During these tests, experimenters noted that the model was marginally stronger in one test. This result has been attributed to the fact that the impact velocity on the model was higher resulting in higher strain rates and thereby increasing the strength of the model material.

Another interesting item in these tests is that the steel modeling was done quite poorly. The model steel had a 10% difference in ultimate strength and a 30% difference in yield strength compared with the prototype steel. As well, smooth wire was used because it was less expensive, although pull-out tests had indicated a 21% loss in pull-out strength as compared with deformed wire. In spite of this apparently serious inconsistency in modeling, the final results of both the model and the prototype agreed well. This indicates that the impact condition for this test resulted in a specimen failure not dominated by the reinforcing steel behaviour.

A joint project between the Atomic Energy Agency in England (UKAEA) and the Federal Ministry of Research and Technology in Germany consisted of testing full scale and 1/5.6 scale models of missile impact on slabs/18/. Their initial comparisons were not in good agreement. Upon closer examination this inconsistency was found to be a result of poorly modeled material and impact velocities. The English group then built a second series of 1/5.6 scale models with more attention given to modeling the materials and impact conditions. These tests proved very successful. The permanent deflection of the model was found to be 1/5.6 times the prototype deflection, which in terms of strain is 1:1. There was also a good agreement in cracking and damage

patterns, although the model showed slightly less damage in some cases.

These case studies emphasize the importance of properly scaled models in predicting full scale behaviour, and although they do prove the validity of using scale models in reinforced concrete, one cannot absolutely predict if the same will be true for the case of scale drop tests. One reason is that for all these particular cases, the specimens were of a slab or panel type construction and they were always supported by a reaction system. In addition, the impact conditions were generated by relatively small, fast moving projectiles, the velocities ranging from 25 m/s to 260 m/s. In the case of drop tests, although the loading condition is still one of impact, the velocity involved is much lower (13.3 m/s for a 9 m drop) and the load must be carried independently by the specimen through crushing and deforming. As well, although strain rate effects did not play an important role in the case studies presented, they may affect the drop tests.

2.4 Strain Rate Dependency

The effect of strain rate on the individual components of reinforced concrete has been well established. In all cases, as strain rate increases, the strength of both the steel and the concrete has been observed to also increase. Model theory states that the strain rate will increase as a function of the scale factor, that is, for a one-half scale model the strain rate should be double that in the prototype. However, it was suggested in reference 2 and assumed by most other researchers that the effect of strain rate is negligible. As was seen in the previous section, results from tests which ignored strain-rate effects are nevertheless in good agreement with what theory predicts. One cannot be sure if the good agreement is due to the fact that the strain rate was not changing as theory predicted or if the difference in strain rate between model and prototype was not significant. One paper/6/, which examined the effect of strain rate in solid steel blocks of various configurations, determined that for steel the strain rate effect is negligible over a scale factor of four. Concrete, however, is a much less homogeneous material and in order to try to explain the model behaviour rationally the actual strain rates occurring during the drop tests should be measured. A method for determining the material behaviour at high strain rates should be developed. It is for this reason that the effects of high strain rates on steel and concrete properties will be discussed.

The effect of strain rate on steel has been well established for strain rates ranging from 10^2 με/s to 10^7 με/s /19,20/. These tests indicate that the elastic modulus is not affected. The yield strength can increase from 10% to 80% and the ultimate strength from 10% to 40% depending on the type of steel and the strain rate. Normal reinforcing steel, with a yield strength in the range of 300-500 MPa, shows significant increase in both the yield and the ultimate strength only at relatively high strain rates (>10^6 με/s)/19/. These strain rates may be larger than those occurring during the impact tests, which may explain why no effect due to strain rates were observed.

Most of the tests on concrete have been performed at relatively low strain rates (<10^5 με/s), but even so an increase in the compressive strength, peak strain, and secant modulus has been identified/19,21/. The stiffer and stronger concretes, such as those with stiffer aggregates, seem to be less sensitive to rate of loading/19,21/. The increase in compressive strength can range anywhere from 10% for a strain rate of 10^2 με/s to 40% for a strain rate of 10^5 με/s, although one researcher reported no increase in strength for strain rates less than 10^5 με/s /19/.

Shah and Ahmad performed some tests on lightweight and normal weight concrete cylinders at three different strain rates. Based upon their tests, and previous experiments by others, Shah and Ahmad have developed relationships for determining the effect of strain rate on ultimate strength, peak strain and secant modulus/21/. Based on their formulation, for a 40 MPa concrete there would be an increase in strength of 20% for a strain rate of 10^2 με/s and 36% for a strain rate of 10^5 με/s.

As for the effect of strain rate on tensile strength, researchers/19/ have found that the tensile strength also increases with increasing loading rates. Tensile strength seems to be more strain rate sensitive than compressive strength/22/. Based on modulus of rupture tests, the increase in tensile strength can range from 35% for a strain rate of $7x10^2$ με/s to 46% for a strain rate of 2.7×10^5 με/s /22/.

Fracture energy, which is related to the fractured surfaces exposed along a crack (ie, aggregate, mortar, or bond interface) and to the specific surface energies required to separate each of the exposed surfaces, has been shown to also increase as loading rate increases/8/. This suggests that the energy absorbed in fracturing of a scale model will be greater than the prototype since the strain rate in the model will be higher. One would expect the tensile strength, which is directly related to the fracture energy, to increase also.

2.5 Instrumentation and Analysis

In order for a test to be useful in the analysis phase it must be properly instrumented. The applied loading and model response must both be well defined. In the case of the impact tests studied, the applied loading-time histories were determined from load cells attached to either the striking hammer or reaction points and connected to high speed recorders /16,17,23, 24/. Alternatively, the loading history can be derived from acceleration records as determined from either piezo-electric or hanging mass type accelerometers/1,5,6,25,26/ connected to high speed recorders. The force in any direction is determined by multiplying the components of the acceleration and mass in the desired direction. Use of accelerometers is most popular for drop tests.

The impact velocity is another critical parameter which must be measured accurately. This is especially important for missiles since the impact velocity is a variable depending on the charge of the firing mechanism. By far the most popular method for doing this is the use of high speed cameras at speeds on average of about 500 frames/s, although speeds as high as 5000 frames/s have been used for high-velocity missile impacts/23/. Photo-electric switches are also popular, and in one instance carbon break rods and impact foil gauges were also used/17/.

Deformation measurements for impact tests are difficult to make. In one case, displacement transducers were used to measure deflections/23/; however, this is not practical for drop tests. Strain gauging in steel cask drop tests has proved successful/6/, and good results have been obtained in one reinforced concrete drop test specimen where strain gauges were placed on the reinforcing bars/1/.

Assessment of damage is made primarily in a subjective manner by investigating the crack patterns, spalled area, volume and size distribution of spalled material, depth of perforation, and amount of backface scabbing (in the case of missile impacts on slabs). This method is useful for a qualitative estimate of damage; however, it is not very useful if numerical analysis is required.

In the case of missile impact tests, the two most popular methods of analysis are to compare the observed behaviour of the test specimens with empirical formulas for the depth of perforation and/or the results from a finite element/finite difference program/16,17,18,23,24,27/. Simplified methods of analysis which give approximate results include idealizing the test

arrangement as a one degree of freedom system subjected to triangular pulse loads/16,20/. Another fast and simple method involves using impulse and energy conservation laws based on a linearly elastic system, although these can be conservative /19,28,29/. One final method for trying to understand the behaviour of a test specimen is to compare the strain energy of the static response to the strain energy of the dynamic response/19,22,24/. This method requires that the specimen can be analysed statically and also it requires a load-deformation curve for the impact tests. From the load-deformation curve, the strain energy can be determined by integrating the area under the curve.

No attempts have been made to define the stress-strain state of the models, or to account for the effect of strain rate on the constituent materials of the models. This is primarily due to the fact that no quantitative measurements have been made in these areas to allow computational methods to be employed.

3.0 TEST SERIES PROPOSAL

The literature search makes it clear that the use of scale model testing for reinforced concrete structures is a valid tool, and in the case of fast moving projectiles impacting on reinforced concrete panels, test results indicate that scale model behaviour gives a very good representation of prototype behaviour. It cannot be clearly answered, however, if for drop tests, the agreement between model and prototype behaviour will be as good. The principal reasons being that the impact force is a variable which depends on the mass of the specimen, the impact velocity is much lower than in the tests previously studied, and the specimen must carry the load independently. Therefore, it is recommended that a test series be carried out to determine if there are any scale effects, outside of those predicted by theory. The following is the test series proposed to answer this question.

3.1 Test Specimen Shape and Size

The test specimen shape chosen is as in Figure 1. This cylindrical ring shaped specimen was chosen for several reasons. The primary reason is that this specimen shape exhibits many of the types of behaviour previously observed for drop tests. Similar to two concrete containers previously tested/1,5/, this specimen will undergo crushing at the impact point and tensile cracking away from the impact point. In addition, bending and shear deformation will also be prominent components of the behaviour. The second reason for this choice of specimen is that it has approximately the same ratio of diameter to wall thickness as

that of the most recent proposed concrete cask design/30/. One further advantage of this specimen shape is that it can be analysed statically using a non-linear frame analysis program. This feature will be useful in the analysis phase to allow comparisons to be made between the static and dynamic behaviour.

The dimensions chosen for the specimens are given in Table 2. These final dimensions were arrived at after considering various possibilities for the specimen sizes based on possible reinforcing steel choices (see Appendix A). The proportion of the inner and outer diameter and wall thickness is based on keeping the model shape similar to the proposed concrete cask design. The length of the cylinder was chosen so as to provide a suitably stable condition at impact, and to adjust the reinforcement ratio to a value similar to that of the proposed cask. Note that although the test specimens are similar to the proposed cask, one will not be able to directly relate the results of the model drop tests to the cask behaviour. The reason is that such aspects as inner and outer steel liner, lid design, end enclosures, and reinforcement arrangement could not be practically modeled in this test series.

3.2 Materials

3.2.1 Steel

The size of the specimens, although small, still allows ordinary reinforcing bars to be used. This is desirable because it will limit distortion of results due to stress-strain behaviour dissimilarities. To get a wider scale range, small diameter deformed fabric wire steel will be used for the smallest model. The small diameter fabric wire will also be used as the ties in most cases, except for the smallest specimen for which plain wire will be necessary. The resulting reinforcing ratio is 1.7%. A list of the proposed steel to be used can be found in Appendix A.

The deformations on the fabric wire consist of indentations as opposed to lugs on the normal reinforcing bars. Most of the specimen will be in compression and so the dissimilarity in deformations should have little effect since the steel deformations are most critical in the tension zones. In the tensile region, cracking is expected to consist of one or two large cracks; therefore, what is most critical is that the full strength of the bars can be developed rather than the bond characteristics. Developing the full bar strength is not a problem since all bars form closed hoops; as well, the deforma-

tions are such that the full strength is developed. Since uniform cracking is not expected to develop perpendicular to the ties, it is not critical whether smooth wire or fabric wire is used for the ties as long as their full strength can be developed.

3.2.2 Concrete

The concrete mix which will be used is a high strength, normal-density concrete. The coarse aggregate will be crushed limestone of 20 mm maximum aggregate size and the fine aggregate will be normal construction sand with 5 mm maximum aggregate size. Although this concrete will have a lower density than the concrete used for the proposed cask design, the test series will still demonstrate the scalability of reinforced concrete under drop test impact conditions. The reason being that both the theory/2,3,4,5/ and the previous tests/16,17,18/ support the validity of scale model test results as long as the material behaviour for both the prototype (full scale specimens) and the models (1/1.22, 1/1.73, and 1/3.94 scale specimens) is the same, regardless of the material (high-density or normal-density concrete) from which they are constructed. The choice of normal-density concrete is preferred because it facilitates the test series with regards to the availability of the required aggregate sizes, and it reduces the amount of work required in grading the aggregates and making the concrete mixes.

In order to be able to scale the coarse aggregates for each concrete mix of the four scale models, it was decided to choose a 20 mm maximum coarse aggregate for the largest model. This choice enables us to use available screened maximum aggregate sizes of 14, 10, and 5 mm for the 1.22, 1.73, and 3.94 scale models, respectively. Although the maximum aggregate sizes are not scaled exactly, the approximate sizes are acceptable given the variability and uncertainty of the concrete properties affected by the coarse aggregate size. A principal concrete cover of 30 mm (labelled C_1, in Figure 1) was chosen based on providing sufficient space between the reinforcement and forms to avoid creating honeycombs or voids. This requirement can be achieved with the chosen maximum aggregate sizes if super-plasticizers and/or vibrators are used when casting the specimens /ACI 38 IM-83/. The side cover (labelled C_2 in Figure 1) was chosen as 40 mm in order to adjust the reinforcement ratio and obtain the desired reinforcement spacing.

The large size differential between the maximum coarse aggregate for each model, and the fact that the water/cement ratios are quite low, requires that some trial concrete batches be made to

ensure that the strength properties of the various mixes are identical. Should the strength change due to the reduced size of the maximum coarse aggregate, then adjustments will have to be made to the water/cement ratio in order to get the same stress-strain behaviour. Alternatively, control test cylinders from the mix for each specimen can be tested at given intervals and the specimen dropped when the cylinder strength reaches the value of the previous tests. This method has the disadvantage that scheduling becomes a problem, and so trial batches of the proposed mixes is recommended.

3.4 Instrumentation

The type of instrumentation desired for a test of this nature is as follows:

- high speed cameras
- video recorders
- 35 mm still camera
- accelerometers
- strain gauges

The Electrical Research Department of Ontario Hydro is in possession of a high speed movie camera which could be made available for the purpose of the tests. The Civil Research Department has available a video recorder and a 35 mm still photograph camera. Piezo-electric high "g" accelerometers and the expertise required to mount and operate them are available from the Mechanical Research Department. The accelerometers available from Mechanical Research require external charge amplifiers and this will detract from the accuracy of the readings if the lead wires connecting the accelerometer and charge amplifier are very long, as they will be in the case of drop tests. Accelerometers with charge amplifiers at the source are available from suppliers and Civil Research will purchase three of these.

Strain gauges have been proven to operate well under impact conditions/1,6/. The strain gauges would have to be purchased by Civil Research, but the equipment required to monitor and record them is available from the Mechanical Research Department. The locations of the accelerometers and strain gauges are as shown in Figure 2. The amount of instrumentation will be reduced for the smaller models (3 and 4) due to concerns about the weight of the hanging cables imparting some undesired motion to the specimen. These concerns are valid and it may be

necessary to provide some type of guidance system to ensure that the model impacts in the correct orientation.

3.5 Test Site Location

The most convenient and suitable site available at the Kipling Research Complex for drop testing the specimens is Mechanical Research's "drop test" facility. The problem with this site, however, is that the facility was designed to handle test specimens dropped when suspended from a cable so that the impact force is taken by the cable and transferred via a series of cross-beams to the supporting columns. Additionally, the maximum drop height for this facility is limited to 6 m. The floor itself was not designed to take a direct impact, and so some analysis is required to determine what modifications can be made to increase the capacity of the floor.

Analysis of the proposed specimen of maximum weight and the resulting impact force have shown that with the addition of a 200 mm (8") steel plate anchored to the concrete floor, an armouring effect is produced which ensures that the impact force is sufficiently distributed so as not to exceed the permissible bearing stress of the floor. The analysis indicates that, even with a 634 kg specimen dropped from a 9 m height, the stress acting on the concrete floor is only 13.3 MPa. This is considerably below the 20 MPa maximum bearing stress permitted by the concrete design code CAN3-A23.3-M84.

Another possible site for dropping the specimens is the pit in the Mechanical Research Structural Laboratory. This pit, 6.7 m x 6.7 m wide and 4.5 m deep, was designed to accommodate a triaxial shaker bed, but it is currently empty. The pit floor has a 200 mm reinforced concrete slab and there is no concern with accidental damage to this floor. In order for this floor to provide the required unyielding target, an additional reinforced concrete pad armoured with a steel plate would have to be constructed. This option requires more work in preparing the target than the first option, but it allows for a 9 m drop height.

4.0 SUMMARY AND CONCLUSIONS

In response to a question as to the validity of using scale concrete models to predict full scale prototype behaviour, particularly for the case of drop test impact loading, a literature search was conducted.

The principal findings of the literature search are as follows:

(1) Scaling laws exist for modeling reinforced concrete; however, special care must be taken to model both the concrete and the steel material properties correctly.

(2) For impact conditions where large deformations are expected "replica" scaling must be used. This requires that the materials for the model and prototype have identical stress-strain characteristics.

(3) Care must be taken to model the bond characteristics of the steel, as well as the cracked characteristics of the concrete (ie, aggregate interlock).

(4) Correct modeling of concrete is more critical when crushing is the dominant failure mode and correct modeling of the steel is more critical if the section is lightly reinforced and there will be significant steel yielding.

(5) Modeling of concrete panels under impact conditions where models of different scales were tested has confirmed the scaling laws.

(6) There is nothing in the literature to indicate that modeling of concrete specimens under drop test conditions is not valid, although no such tests on models of different scales have been done.

(7) High strain rates increase the yield strength of steel, but do not affect Young's modulus.

(8) High strain rates increase the ultimate strength of concrete both in tension and compression, as well as increasing the peak strain and secant modulus slightly.

(9) Better instrumentation of the models is required to clearly define the behaviour.

For the particular case of drop tests, very limited information is available. Therefore, an experimental program designed to verify the scaling laws under these more severe impact conditions has been proposed. The program is to consist of drop testing a series of reinforced concrete specimens of different scales. The proposed specimens are essentially short, open-ended cylinders (Figure 1). The aspect ratio (R/t) of the cylinders is similar to the proposed concrete cask design; however, more importantly, this shape was chosen so as to

incorporate many structural responses. Local crushing will be experienced at the impact point, tensile cracking will occur away from the impact point, and shear and bending deformations are expected. The specimen sizes would range from a full scale control model (prototype) to models with scale factors of 1.22, 1.73 and 3.94 (see Table 2). If time and budget permit, a second specimen of each size would be tested to verify the results of the first drop tests. The proposed instrumentation for each specimen consists of strain gauges bonded to the circumferential reinforcing bars and accelerometers mounted to the exterior of the specimen. High speed photography and video recording of the tests are also recommended. The drop tests will be conducted in the Mechanical Research Structural Laboratory.

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REFERENCES

1. Sato, J., Vecchio, F.J., "Concrete Integrated Cask Program Structural Testing of a 1/2 Scale Model, Parts 1 and 2" Ontario Hydro Research Division Reports, No. 85-64-H, No. 85-123-H.

2. Zia, P., White, R.N., Vanhorn, D.A., "Principles of Model Analysis", Models for Concrete Structures ACI Publication SP-24, 1980, pp. 19-39.

3. "Pipe Missile Impact Experiments on Concrete Models", EPRI Project NP-1883, Research Project 393-1, Appendix A.

4. Abrams, P.D., "Behaviour of Small Scale Reinforced Concrete Model Structures", Dynamic Modelling of Concrete Structures ACI Publication SP-73, 1982, pp. 65-82.

5. Merret, G.J., "Scale Model Testing of a Concrete Canister." AECL Report WNRE-452, December 1980.

6. Donelan, P.J., Dowling, A.R., "The Use of Scale Models in Impact Testing" The Resistance to Impact of Spent Magnox Fuel Transport Flasks, Mechanical Engineering Publication Ltd., 1985.

7. Davies, L., "Damaging Effects from the Impact of Missiles Against Reinforced Concrete Structures," Nuclear Energy, Vol. 19, No. 3, June 1980.

8. Zielinski, A.J., "Model for Tensile Fracture of Concrete at High Rates of Loading," Cement and Concrete Research Vol. 14, 1984.

9. Hughes, B.P., Gregory, R., "Concrete Subjected to High Rates of Loading in Compression", Magazine of Concrete Research, Vols. 23-25, March 1972.

10. Mindess S., Young F., Concrete. Pg. 120-125, 398-399. Prentice-Hall. 1981.

11. Neville, A.M., Properties of Concrete. Pitman Publishing Ltd. 1981.

12. Bresler (ed), Reinforced Concrete Engineering, Vol. 1 Materials, Structural Elements, Safety. John Wiley and Sons, New York, 1977.

13. Cordon, W.A., Gillispie, H.A., "Variables in Concrete Aggregates and Portland Cement Paste Which Influence the Strength of Concrete," ACI Journal, August 1963.

14. Harris, H.G., Sabnis, G.M., White, R.N. "Reinforcement for Small Scale Direct Models of Concrete Structures," ACI Publication SP-24, 1980, pp. 141-158.

15. Andre, H.M., Collins, M.P. "Toronto/Kajima Study of Scale Effects in Reinforced Concrete", MASc Thesis, University of Toronto, 1986.

16. McHugh S., Gupta Y., Seaman L., "Pipe Missile Impact Experiments on Concrete Models", EPRI Research Project 393-1, NP-1883.

17. "Scale Modelling of Turbine Missile Impact into Concrete" EPRI Report NP-2746.

18. Sage F., Pfeiffer A., "Response of R.C. Targets to Impacting Soft Missiles An FRGMRT-UKAEA Co-Operation in Tests to Validate Computer Codes and Scaling Laws", 5th Int. Conf. on Str. Mechanics in Reactor Technology, Article J8/4, 1979.

19. "The Effect of Impact Loading on Building", 21-1L RILEM Committee.

20. Brandes K., Limberger G., Herter J., "Strain Rate Dependent Energy Absorption Capacity of Reinforced Concrete Members under Aircraft Impact", 7th International Conference on Structural Mechanics in Reactor Technology, Article J9/5, 1983.

21. Ahmad S., Shah S., "Behaviour of Hoop Confined Concrete Under High Strain Rates", ACI Journal, No. 5 Proceedings, V. 82, Sept-Oct, 1985.

22. Suaris W., Shah S., "Properties of Concrete Subjected to Impact", Journal of Structural Engineering, Vol. 109, No. 7, July, 1983.

23. Uchida T., Tsubota H., Yamada T., "Experimental Investigations on Reinforced Concrete Slabs Subjected to Impact Loading", 8th International Conference on Structural Mechanics in Reactor Technology, Article J5/1, 1985.

24. Barr P., Brown M., et al., "Studies of Missile Impact with Reinforced Concrete Structures", Nuclear Energy, Vol. 19, No. 3, June 1980.

25. Wachtell G.P., "Drop and Fire Tests on 1/2 Scale Model of TN-9 Shipping Container", 4th International Symposium on Packaging and Transportation of Radioactive Materials, 1974.

26. Marchal A., Swindell G.E., "Catalogue of Facilities in Member States of the European Community for Testing the Packaging of Radioactive Materials", Nuclear Science and Technology, 1983.

27. Ohnuma H., Ito C., Nomachi S.G., "Dynamic Response and Local Rupture of Reinforced Concrete Beam and Slab Under Impact Loading", 8th Int. Conf. on Str. Mechanics in Reactor Technology, Article J5/3, 1985.

28. Burcharth H., "Full Scale Dynamic Testing of Dolosse to Destruction", Coastal Engineering, Vol. 4.

29. Stangenberg F., Buttmann P., "Impact Testing of Steel Fibre Reinforced Concrete Slabs with liner", 5th Int. Conf. on Str. Mechanics in Reactor Technology, Article J7/5, 1979.

30. Private Communication with Richard Fong, Ontario Hydro, July, 1986.

TABLE 1*

SCALING OF VARIABLES

Variables	Prototype	Model
Length	L	L/S_ℓ
Displacement	x	x/S_ℓ
Strain	ε	ε
Stress	σ	σ
Force	F	F/S_ℓ^2
Time**	t	t/S_ℓ
Strain rate	$\dot{\varepsilon}$	$\dot{\varepsilon}S_\ell$
Velocity	V	V
Energy	e	e/S_ℓ^3
Acceleration	a	aS_ℓ
Gravitational acceleration	g	gS_ℓ
Density	ρ	ρ
Mass	M	M/S_ℓ^3
Young's modulus	E	E

S_ℓ = scale factor > 1.
** = Any characteristic time of the material.
*Reference 4

TABLE 2*

SPECIMEN PARAMETER SUMMARY

Model ID	Scale Factor	Main Steel		Tie Steel		Maximum Coarse Agg Size mm	R_1 mm	R_2 mm	t mm	L mm	C_1 mm	C_2 mm	V m^3	M kg
		ID	Ø mm	ID	Ø mm									
1	1	20 M	19.5	10 M	11.3	20	300	500	200	525	30	40	0.264	634
2	1.22	15 M	16.0	D10	9.0	14	245	410	165	430	25	33	0.146	350
3	1.73	10 M	11.3	D5	6.4	10	170	285	115	303	17	23	0.050	120
4	3.94	D3	4.95	WIRE	3.0	5	75	125	50	133	8	10	0.004	10

* See Figure 1 for specimen dimension identification.

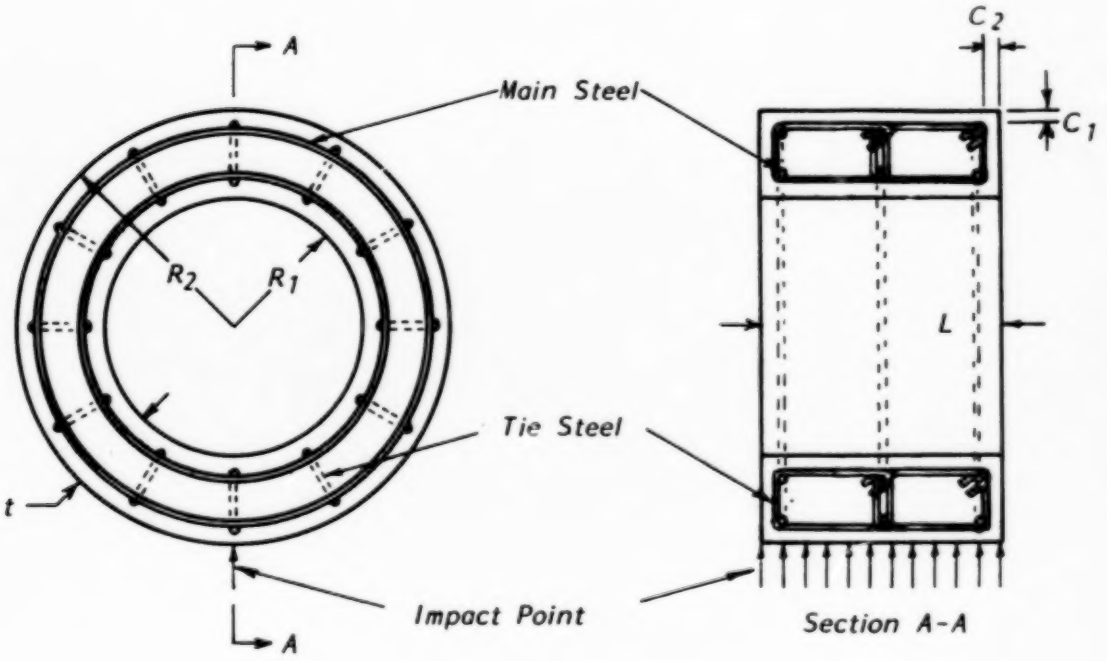

FIGURE 1
SPECIMEN SHAPE AND REINFORCEMENT DETAILS

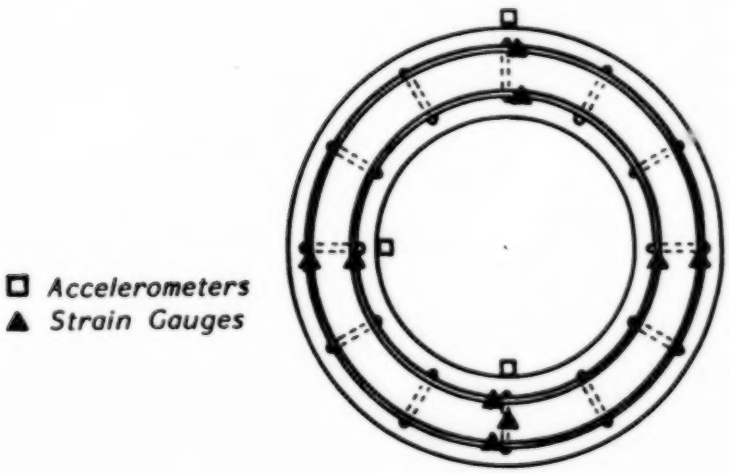

FIGURE 2
INSTRUMENTATION PLACEMENT

APPENDIX A

PRELIMINARY TEST SERIES DETAILS

Test Series	Steel: Long ID	Steel: Long Ø mm	Steel: Ties ID	Steel: Ties Ø mm	* Scale Factor	Max Coarse Agg. Size mm	R_1 mm	R_2 mm	t mm	L mm	V m^3	M** kg	Comments
A	25 M	25.2	10 M	11.3	1	20	375	625	250	250	0.196	718	-25 M bar unreasonable for specimen of this size
	15 M	16.0	D 6	7.0	1.58	12.7	240	400	160	160	0.051	188	
	10 M	11.3	D 3	5.0	2.23	9.0	165	275	110	110	0.018	65	
B	20 M	19.5	10 M	11.3	1	20	300	500	200	200	0.101	368	
	15 M	16.0	D 10	9.0	1.22	16.4	245	410	165	165	0.056	205	-not a big scale range
	10 M	11.3	D 5	6.4	1.73	11.6	170	285	115	115	0.019	69	
C	20 M	19.5	10 M	11.3	1	20	300	500	200	200	0.101	368	
	10 M	11.3	D 5	6.4	1.73	11.6	170	285	115	115	0.019	69	-smallest specimen too light
	D 3	4.95	WIRE	3.0	3.94	5.1	75	125	50	50	0.002	5.7	
D	15 M	16.0	D 10	9.04	1	15	250	415	165	165	0.057	208	-smaller models, bars are of different deformations
	D 12	9.91	D 4	5.72	1.61	9.3	150	250	100	100	0.013	46	
	D 3	4.95	WIRE	3.0	3.23	4.6	75	125	50	50	0.002	5.7	-smallest specimen too light
E	20 M	19.5	10 M	11.3	1	20	300	500	200	300	0.151	552	-good scale range
	15 M	16.0	D 10	9.0	1.22	16.4	245	410	165	245	0.083	304	-most bars of same deformations
	10 M	11.3	D 5	6.4	1.73	11.6	170	285	115	170	0.028	102	-ties have diff. deformations
	D 3	4.95	WIRE	3.0	3.94	5.1	75	125	50	75	0.002	8.6	but their bond characteristics are not significant
F	SAME AS "E" EXCEPT L IS INCREASED									400	0.201	736	-bearing area increased
										330	0.112	410	-stability increased
										230	0.038	138	-smallest specimen is of reasonable weight
										100	0.003	11.5	
G	SAME AS "F" EXCEPT L IS INCREASED									525	0.264	634	-bearing area increased
										430	0.146	350	-steel can be more easily accommodated
										303	0.050	120	
										133	0.004	10	-normal-density concrete simplifies concrete mix requirements

* based on longitudinal steel

** based on high density concrete (ρ = 3650 kg/m^3) except for test series G which is based on normal density concrete (ρ = 2400 kg/m^3)

MATERIALS

Steel:

(i) Normal reinforcing bars; fy = 400 MPa (58 ksi)

Bar No.	Diameter (mm)	Cross-Sectional Area (mm^2)
20 M	300	19.5
15 M	200	16.0
10 M	100	11.3

(ii) Deformed fabric wire; fy = 480 MPa (70 ksi)

ID	Diameter in	Diameter mm	Cross-Sectional Area (mm^2)
D 10	0.356	9.04	64
D 5	0.252	6.40	32
D 3	0.195	4.95	19

(iii) Fabric wire available

0.1196" wire = 3.038 mm

Concrete:

A normal-density (p ≈2400 kg/m^3) concrete mix will be used, made of;

(i) Coarse: 20 mm maximum crushed limestone.

- material available at Civil Research
- pre-screened aggregates are also available to be used for scaled specimens

(ii) Fine: Normal construction type sand will be used for both full scale and scaled models

- material available at Civil Research